

A METHOD OF SLITLESS ABSOLUTE SPECTRAL PHOTOMETRY

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SUMMARY

A discussion of absolute slitless spectrophotometry for reentry and astronomical radiation measurements is given. A method of photometry intended for 20-percent accuracy for moderate-aperture (5 to 30 centimeters) slitless spectrographs is presented. This accuracy is a factor of 5 reduction in errors over previous absolute spectrophotometry using similar instrumentation for which accuracy statements have been published. The method of photometry has been applied to a spectrogram of the star Vega and has yielded spectral irradiance values, in the wavelength interval from 4200 to 6200 angstroms, with an average deviation of 7.9 percent from values in the literature. The maximum deviation of any of the points, taken at 100-angstrom intervals, was 16.3 percent.

INTRODUCTION

Quantitative spectral data of atmospheric entries and reentries can contribute greatly to the understanding of reentry processes, the meteoroid hazard problem, and other space and atmospheric phenomena. With the advent of intercontinental ballistic missiles, considerable effort has been spent in obtaining spectra from reentering rocket payloads. Several attempts have been made to obtain spectral data with large tracking telescopes or slit telespectrographs, but the target acquisition and tracking problems have proven to be very difficult. Slitless spectrographs reduce the target acquisition and tracking problems by 2 to 4 orders of magnitude. Consequently, the most usable data so far have come from moderate-aperture (5 to 30 centimeters) slitless spectrographs.

However, work in the field of absolute spectral photometry for slitless spectrographs has been very limited and relatively little effort has been spent on calibration and reduction of slitless spectrograms. Dr. Allan F. Cook of the Harvard College Observatory pioneered the work in absolute slitless spectrophotometry and has published, with Peter M. Millman, photometric reductions and analyses of two meteor spectrograms in references 1 (in 1955) and 2 (in 1959). Data reduction of reentry spectrograms from

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the Eastern Test Range and the Western Test Range has been contracted out to data-reduction agencies and virtually no reduced data have been published for general distribution. Reference 3 contains a discussion of the large quantity, computerized approach of one company and reference 4 contains the statement: "Laboratory studies indicate that absolute intensities may be measured photographically under field conditions to within a factor of 2 accuracy." Reference 5 presents quantitative spectral data by the method of reference 1 of two Trailblazer I payload reentry events, with a factor of 2 accuracy.

A method of absolute slitless photometry has been developed and a spectral sensitizer built, both of which were designed for 20-percent photometry in the visible region of the spectrum of photographable reentries. A description of the method of reduction and calibration is the subject of this paper.

METHODS OF PHOTOMETRY

A complete reduction of a slitless spectrogram may be divided into two parts: the determination of the wavelength of the radiation and the determination of the intensity of the radiation as a function of wavelength. A combination of techniques is generally used to determine wavelength. A dispersion scale is constructed with the aid of the grating equation:

$$d(\sin i \pm \sin \theta) = n\lambda \quad (1)$$

where

- d average spacing between two adjacent grooves of diffraction grating
- θ angle of diffraction, that is, angle between camera optical axis and dispersed radiation of wavelength λ
- i angle of incidence, that is, angle between camera optical axis and zero-order image
- n order number
- λ radiation wavelength of interest

The dispersion scale is adjusted to agree with reference-line spectra, such as from a mercury source, or is adjusted to agree with identified radiation of the spectrum being reduced. Line radiation is generally checked by wavelength with tables such as those in references 6 and 7 and band radiation is generally checked by wavelength with reference 8.

The determination of irradiance as a function of wavelength is more difficult and involved than the determination of the wavelength of the irradiance. The irradiance recorded by an imaging optical system and a photosensitive emulsion can be expressed by an equation of the form

$$H_{\lambda} = f \left[D_{\lambda}, \frac{1}{t_1}, \frac{1}{T(\theta)_{\lambda}}, \frac{1}{G(\theta)_{\lambda}}, R(t_1, t_2) \right] \quad (2)$$

where

H_{λ} spectral irradiance, rate of transfer of radiant energy per unit incident area per unit wavelength interval

H_{λ}' known spectral irradiance

t_1 time of exposure to H_{λ}

t_2 time of exposure to H_{λ}'

D_{λ} film density

E_{λ} atmospheric extinction

$T(\theta)_{\lambda}$ camera transmission

$G(\theta)_{\lambda}$ grating transmission

$R(t_1, t_2)$ reciprocity-failure correction

The functional forms of D_{λ} , E_{λ} , $T(\theta)_{\lambda}$, $G(\theta)_{\lambda}$, and $R(t_1, t_2)$ are complicated and are usually empirically determined, either singly or in combinations. D_{λ} can be expressed as

$$D_{\lambda} = f' \left[H_{\lambda}', t_2, E_{\lambda}, T(\theta)_{\lambda}, G(\theta)_{\lambda} \right] \quad (3)$$

The D_{λ} for a range of $H_{\lambda}'t$ can be plotted in logarithmic form to give film calibration H and D (Hurter and Driffield) characteristic curves.

In general, there will not be enough information on a spectrally dispersed negative of a reentry event to allow an irradiance calibration. The necessary information can be put on film by a sensitometer. The method of photometry used by Dr. Cook for meteor spectra is given in references 1 and 2. Dr. Cook designed and had built a spectral sensitometer which is used to obtain H and D curves for film as a function of wavelength. The

source for this sensitometer is a tungsten ribbon-filament lamp. By using the spectrum of a standardized star on the same negative as the spectrum to be reduced, a calibration of the atmosphere-camera-grating is obtained. Corrections for differences in optical paths traversed by the radiation from the star and the reentry and for different exposure times are then made. The weakest point in this approach is the small probability of having a good first-order spectrum of a standardized star near the reentry image.

The method of photometry discussed in reference 4 uses essentially the same type of sensitometer as Dr. Cook's to obtain H and D curves and then applies separate corrections for atmospheric extinction, camera, and grating. The calibrations are performed in a laboratory and not in the field. The photometry in reference 3 is similar to, but not as rigorous as, that of reference 4. Perhaps the weakest point in this approach is the determination of atmospheric extinction. Atmospheric extinction is obtained from model-atmosphere tabulations or statistical data. However, model-atmosphere and statistical data cannot be considered a good substitute for direct measurements in view of the large corrections that are necessary for low-elevation-angle events and for other than ideal weather conditions.

The primary standard used in the presently reported method of photometry is a standard of spectral irradiance as opposed to a standard of spectral radiance (rate of transfer of radiant energy per unit solid angle per unit area from the source per unit wavelength interval) used in the other two methods. Since photometry is basically an irradiance measurement, that is, for slitless applications the quantity incident on or into the sensor is irradiance, a comparison of the unknown irradiance with a known amount of irradiance is the most direct means of measurement. With a radiance standard, each optical element in the sensitometer is usually calibrated. These calibrations generally include a slit, a grating, lens elements, the film, and the physical dimensions of the sensitometer. Only a calibration of the irradiance from the sensitometer and a calibration of the combined film-camera-grating system are needed with the presently reported method of photometry.

INSTRUMENTATION

Sensitometer

The sensitometer serves as a field or secondary irradiance standard for the photometry of this paper. A photograph and sketch of the spectral irradiance sensitometer which was used in the intensity calibration reported in this paper are presented as figure 1. The sensitometer consists of radiation sources, an exposure control mechanism, power supplies, and collimating optics in a wooden cabinet 36 by 50 by 183 centimeters. The radiation source for irradiance calibration is an alternating-current quartz-iodine coiled-tungsten-filament lamp. The radiation source for wavelength calibration is a

quartz low-pressure mercury-discharge lamp. A 35-millimeter camera body with a metal focal-plane shutter is used for exposure control. The camera body provides fixed exposure times of 1 millisecond to 1 second in 11 steps. A slit, 0.2 by 11 millimeters, is mounted in the focal plane of the camera body, and a piece of ground glass is fixed immediately in front of the slit. Filters are mounted on the front of the camera body.

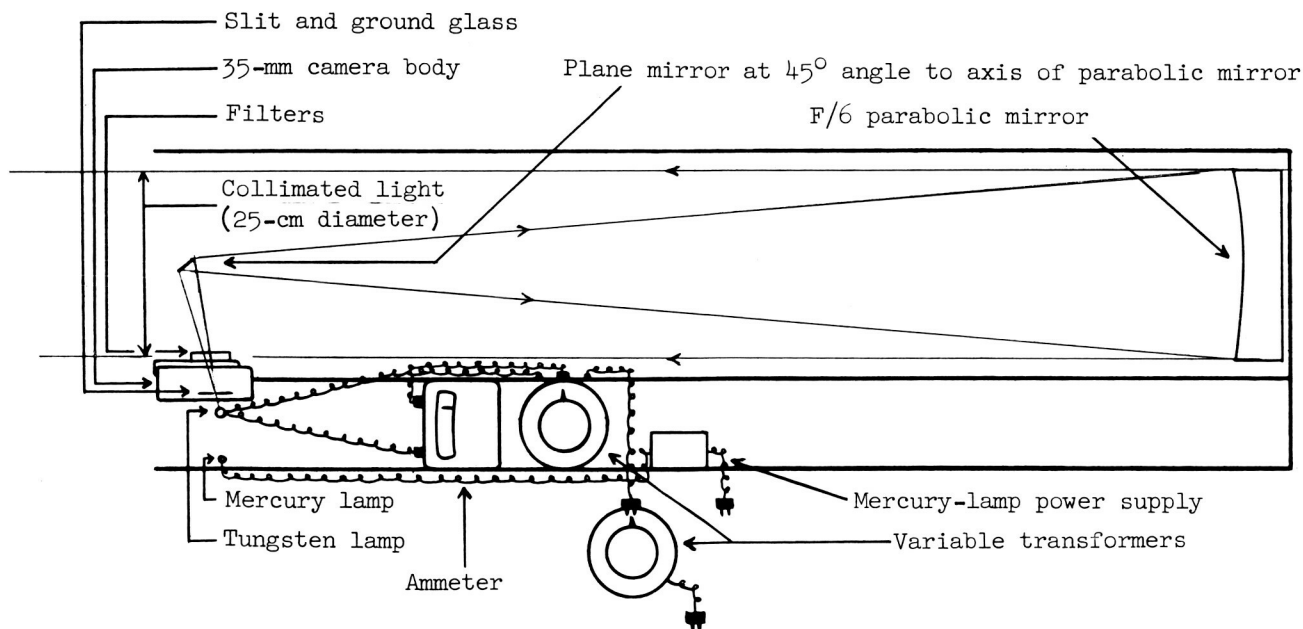
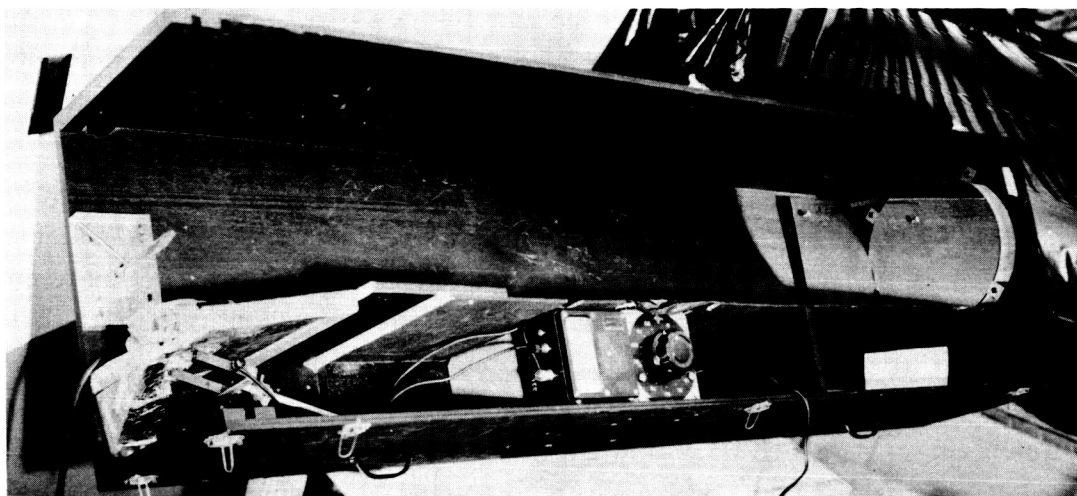


Figure 1.- Photograph and sketch of sensitometer.

L-66-4600

The sensitometer is used to calibrate spectral irradiance from a distant source which arrives at the spectrograph uniform in intensity over the camera aperture. It is desirable, then, that the output of the sensitometer be similar to the quantity to be

measured, that is, that the output of the sensitometer be a uniform beam of parallel light. Light passes from the tungsten lamp to the ground glass which then acts as the source. Light passes from the ground glass through the slit, shutter, and filters to a small plane mirror. The light is reflected by the plane mirror to a 30-centimeter-diameter f/6 first-surface parabolic mirror. Thus the output of the sensitometer is an on-axis parabolic-collimated beam of light roughly 30 centimeters in diameter.

The small mercury lamp, placed behind the tungsten lamp, provides line spectra for dispersion calibration. The wooden cabinet containing the components is painted dull black and the lamp compartment is lighttight.

The irradiance calibration lamp is rated at 200 watts at 6.5 amperes alternating current. Two variable transformers (10 amperes maximum) are connected in series to form a power supply with fine control. A calibrated 5-ampere full-scale ammeter is used to monitor the current which is maintained at 4 amperes. The color temperature of the lamp is low (2400° K) at this current with a steep gradient into the red. Two wratten blue filters, stability BAA, mounted on the front of the camera body, flatten the spectral energy distribution in the visible wavelength region of light from the sensitometer.

The 35-millimeter-camera-body shutter was measured for accuracy and repeatability. The shutter speeds of the camera body and focal-plane slit were measured with a camera motion analyzer. This calibration is presented in table I. The uncertainty of the exposure times is based upon the repeatability of 10 readings. The motion analyzer, however, was designed for calibration of shutter speeds over a large area of the camera focal plane and not for a narrow slit area. Because of this and for other reasons, it was suspected that the motion-analyzer results might not be valid. An arrangement of a phototube and an oscilloscope with type L amplifier was then used to calibrate the

TABLE I.- CALIBRATION OF 35-MILLIMETER-CAMERA-BODY SHUTTER

Exposure setting, sec	Shutter open time, sec	
	Motion analyzer	Phototube oscilloscope
1/1000	1/1075 \pm 5%	0.0010
1/500	1/483 \pm 5%	.0018 \bullet 0.0001
1/250	1/260 \pm 5%	.0033
1/125	1/120 \pm 5%	.0076
1/60	1/55 \pm 5%	.014
1/30	1/30 \pm 5%	.029
1/15	1/13 \pm 5%	.061
1/8	1/7 \pm 5%	.120
1/4	1/4 \pm 5%	.220
1/2	5/8 \pm 5%	.495
1	1 $\frac{1}{8}$ \pm 5%	1.08

35-millimeter-camera body shutter. The oscilloscope trace for a 1-millisecond exposure time is presented in figure 2. The results of the oscilloscope calibration are also presented in table I. The uncertainty for the 2-millisecond exposure time is the root-mean-square deviation of six readings. The maximum deviation from the average exposure time (1.81 milliseconds) was 7.2 percent. The shutter rise time across the slit was approximately 0.15 millisecond.

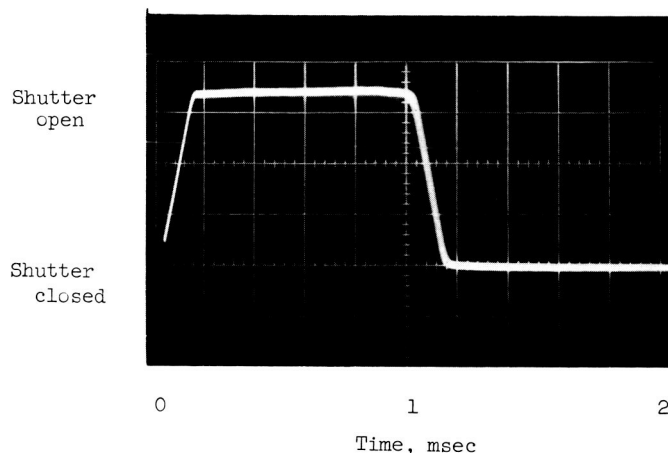


Figure 2.- Oscilloscope trace for sensitometer shutter calibration.

Slitless Spectrographs

A slitless spectrograph is a camera with a diffraction grating or prism placed ahead of the objective lens. The most common slitless spectrographs are ballistic, modified aerial, Schmidt type, and cine cameras with transmission diffraction gratings or prisms. Two slitless spectrographs were used in the work of this paper. The slitless spectrograph used in the calibration of the sensitometer was an $f/2.5$, 178-millimeter focal length, modified K-24 aerial camera with a 400-line/millimeter transmission diffraction grating. The camera has a square 40° field of view, and the camera lens is a four-element Aero-Ektar lens. A K-24 slitless spectrograph is shown in figure 3. The slitless spectrograph used to obtain the spectrogram of the star was an $f/2.5$, 303-millimeter focal length, modified K-37 aerial camera with a 300-line/millimeter transmission diffraction grating. This camera also has a square 40° field of view, and the camera lens is an Aero-Ektar lens.



L-62-5897
Figure 3.- Typical K-24 slitless spectrograph.

CALIBRATION

Sensitometer Calibration

The spectral irradiance from the sensitometer was calibrated against spectral irradiance from a standard of spectral irradiance lamp, calibrated by the National Bureau of Standards (NBS), which was a quartz-iodine lamp with a coiled tungsten filament. Information on this lamp (referred to hereinafter as the standard lamp) may be found in reference 9. The calibration was performed by comparing images produced by radiation from the sensitometer with similar images on the same film frame, produced by radiation from the standard lamp (see fig. 4). Radiation from each source (see fig. 5) was allowed to pass through a slit, become collimated, and be imaged into zero-order and blazed first-order spectrums by a K-24 slitless spectrograph with a 400-line/millimeter blazed transmission diffraction grating. The photometric densities of the images of each source were measured with a high-precision recording microphotometer.

The standard lamp was calibrated for a distance of 43 centimeters from the lamp where the spectral irradiance is approximately 4 orders of magnitude greater than the spectral irradiance from the sensitometer. Since the reciprocity failure for the emulsion was not known to a high degree of accuracy, the radiation recorded from the standard lamp had to be nearly the same in amount as that from the sensitometer. A reduction in radiation from the standard lamp was accomplished by comparing the radiation from the standard lamp at a distance of 1706 centimeters with the radiation from the sensitometer and by using slits of different widths for the standard lamp and the sensitometer.

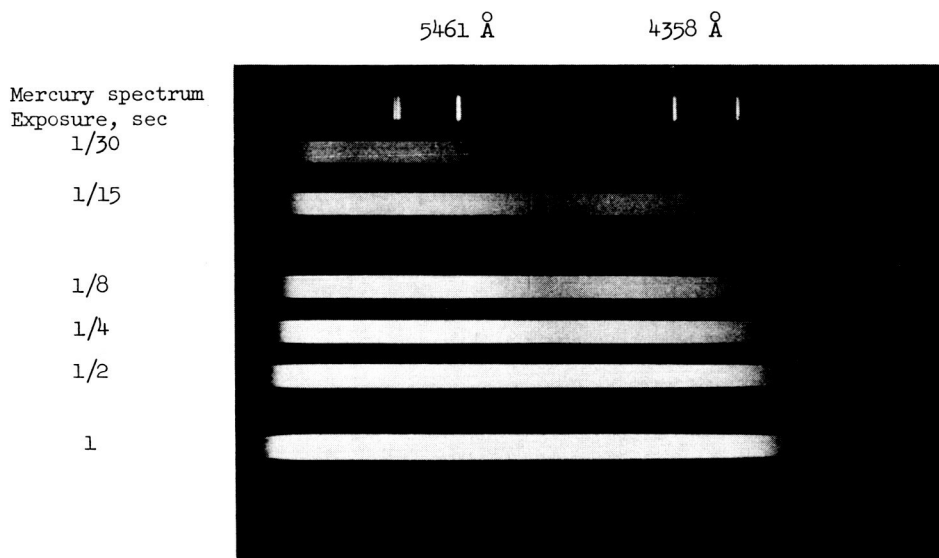


Figure 4.- First-order images of density step wedge from standard lamp and from mercury lamp used in sensitometer calibration. (Exposure times listed are for standard lamp.)

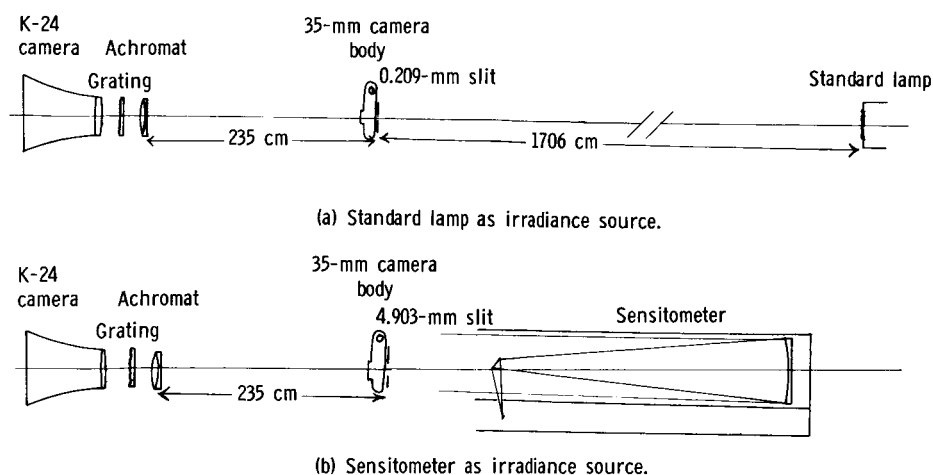


Figure 5.- Sketch of optical arrangement used for calibration of spectral irradiance from sensitometer.

A slit, 0.209 ± 0.005 by 11 millimeters, was placed at the focal point of a 235-centimeter-focal-length collimating achromat to provide line images of the radiation from the standard lamp in the focal plane of the K-24 spectrograph. A slit, 4.903 ± 0.005 by 11 millimeters, was used with the 235-centimeter collimating achromat to provide line images of the radiation from the sensitometer in the focal plane of the K-24 spectrograph. The 4.903-millimeter slit corresponds to a 50-angstrom bandwidth in the K-24 focal plane. The slit widths were measured on a Mann comparator.

A calibrated 35-millimeter camera shutter was used to control exposure times from both sources. Exposure times of radiation from the standard lamp of 1, 1/2, 1/4, 1/8, 1/15, and 1/30 second were used to produce the first-order images shown in figure 4. Monochromatic H and D curves (fig. 6) obtained from the densities of the first-order images produced by the standard-lamp radiation were used for the sensitometer calibration. Exposure times of radiation from the sensitometer of 1, 1/2, 1/4, and 1 second were used to produce first-order images for densitometry. For the same exposure times the radiation through the slit from the standard lamp was approximately 4 times that of the radiation through the slit from the sensitometer. The radiation was incident upon 1 centimeter² or less of the 50-centimeter² aperture of the K-24 spectrograph for this calibration. All first-order images were within 5° of the optical axis of the K-24 spectrograph having a 40° field of view, and no off-axis light-loss corrections (see fig. 7) were applied to the densities of the first-order images. The off-axis light losses for a K-24 Aero-Ektar lens were obtained by placing a photocell in the focal plane of the lens and performing transmission measurements relative to on-axis transmission at 9°, 16°, and 23° from the optical axis. The spectral energy distribution of light from the sensitometer as determined by the calibration is presented in figure 8.

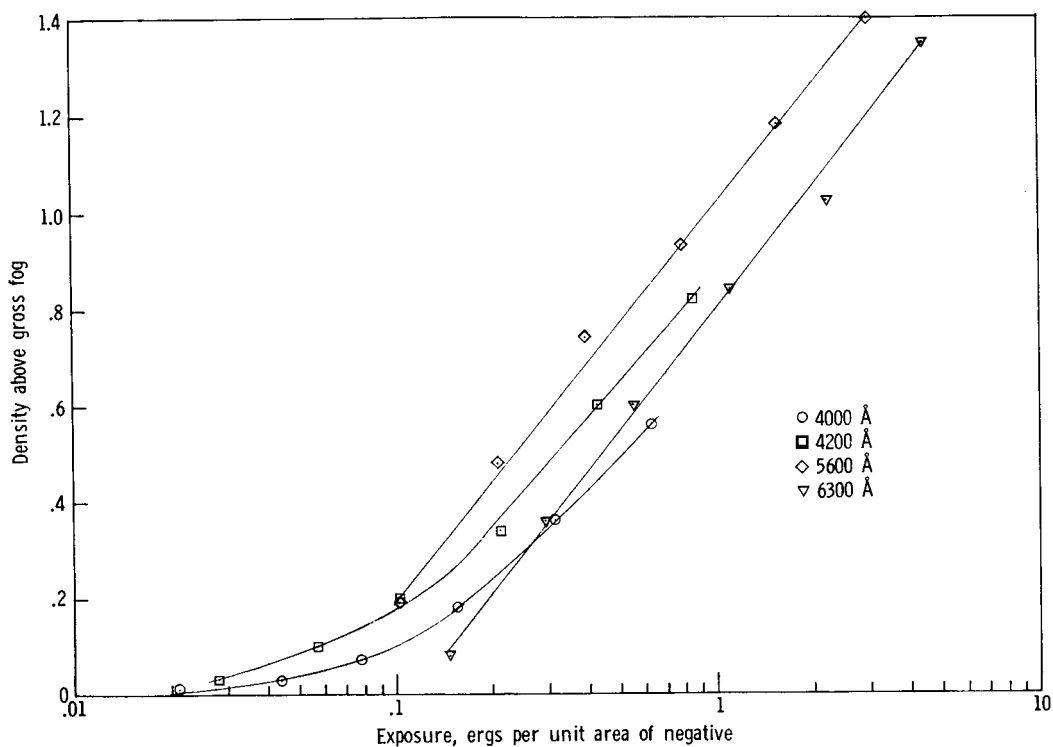


Figure 6.- Representative monochromatic H and D curves obtained from negative for figure 4 and used in sensitometer calibration.

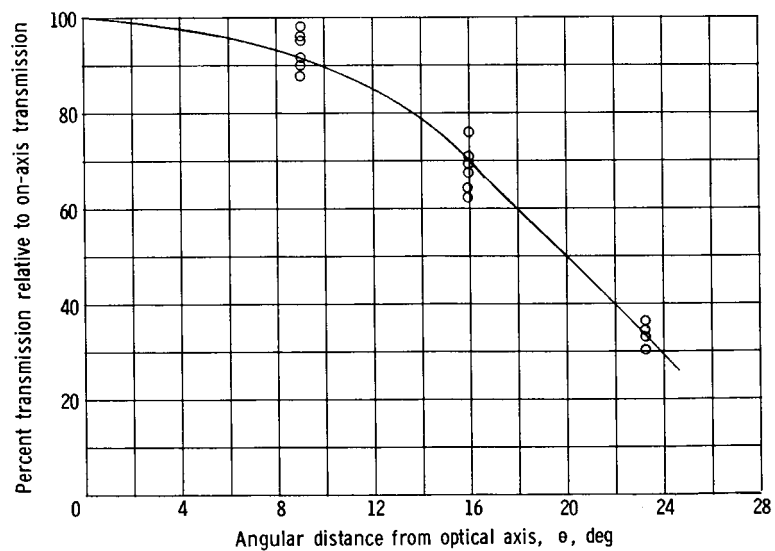


Figure 7.- Empirical curve of off-axis light losses for typical K-24 aerial camera.

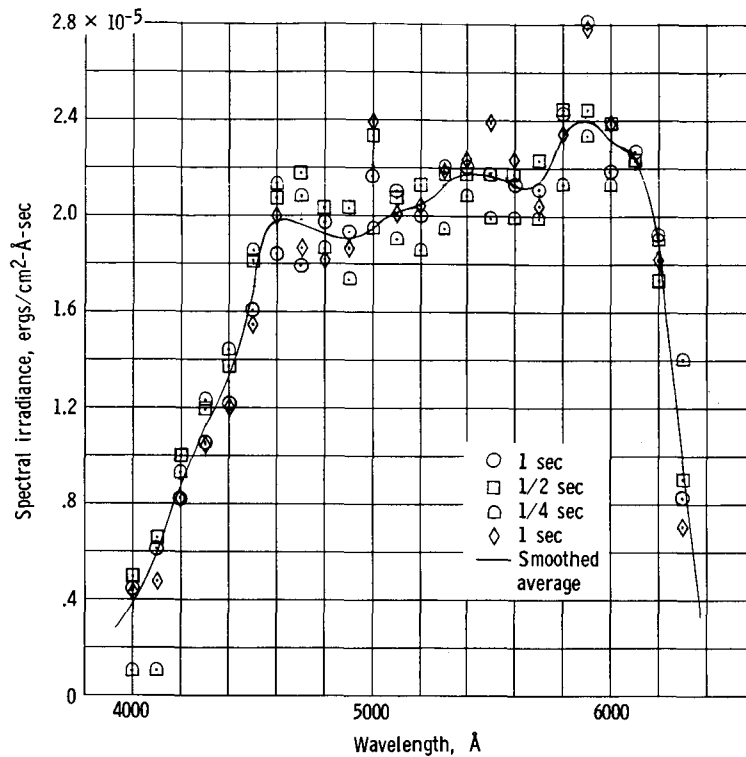


Figure 8.- Absolute spectral irradiance from sensitometer.

Spectrograph Field Calibration

Two primary advantages occur from a field calibration. These are (1) atmospheric attenuation measurements for the time and sky area of the reentry can be obtained and (2) errors arising from exposures having been taken at different times are eliminated. That is, the handling, storage, and exposure history of the calibration film and data film are identical and image change or deterioration resulting from storage, heat, or other causes will automatically be accounted for.

The slitless spectrograph uses an imaging optical system to produce first-order spectrum images from parallel light from the event of interest. The irradiance sensitometer for calibration of slitless spectrographs is shown in figure 1. The spectrograph to be calibrated is placed in front of the sensitometer and aligned so that the objective lens of the spectrograph can be covered with irradiance from the sensitometer. Controlled pulses of irradiance of durations such as 1, 2, 4, and 8 milliseconds are allowed to be incident upon the spectrograph aperture. The optics of the sensitometer and spectrograph are such that the irradiance from the sensitometer is imaged as a set of zero-order lines and blazed first-order spectra of lines of increasing density similar to that shown in figure 4.

The exposure (the product of irradiance and time), in ergs/centimeter²-angstrom at the spectrograph aperture, which produced each density is known. A densitometer trace is made of the blazed first-order images of the slit and the values of transmission for different wavelengths, obtained from the densitometer trace, are plotted against the logarithm of the exposure to give curves. A set of these curves, monochromatic H and D curves, similar to the H and D curves of figure 6 are obtained. The optical path will not be the same for each image and each wavelength; therefore, off-axis light-loss corrections, obtained from figure 7, are applied to normalize all radiation to an on-axis light path.

A densitometer tracing, with all densitometer settings exactly the same as for the sensitometer line images, is made of the first-order image produced by the irradiance to be measured, that is, the unknown irradiance which is recorded on the same or on an adjacent film frame. The exposure for the unknown source can be determined by obtaining the transmission of the unknown source image from the densitometer record at some particular wavelength and then reading the exposure from the appropriate H and D curve. The exposure is then divided by exposure time to give the irradiance of the unknown source. This irradiance must also be normalized to the on-axis light path and corrected for atmospheric extinction. Generally the irradiance is normalized to a distance of 100 kilometers from the source. If a standardized star is in the vicinity of the unknown irradiance source, the difference between the spectral irradiance received at the camera from this star (obtained by performing photometry on the blazed first-order image of the star) and the irradiance from this star outside the earth's atmosphere (the standard way of presenting spectral irradiance from standardized stars) is the atmospheric extinction for the location, time, and sky area of the star and unknown irradiance source. Any difference between the zenith angles of the standardized star and the unknown source is corrected for by using the relation obtained from reference 10

$$\text{Atmospheric extinction} = K \secant z \quad (4)$$

and

$$\Delta \text{ Atmospheric extinction} = K(\secant z_{\text{star}} - \secant z_{\text{reentry}})$$

where z is the zenith angle and K is a constant.

In actual practice, since most reentry spectra are not produced by smooth continuum radiation, it is usually convenient to present the results of the photometry in the form of actual densitometer traces with isometric curves of constant spectral irradiance indicated on the tracing as a function of wavelength. The isometric curves, plotted from H and D curves by determining the transmissions for particular amounts of exposure, are generally normalized to 100 kilometers, outside the earth's atmosphere.

RECIPROCITY FAILURE

The reciprocity law for a photographic emulsion states that the density resulting from light incident on the emulsion is a function of the exposure Ht only and not a function of irradiance H or time t independently. The reciprocity law holds over a wide range of exposure times for most films. However, for long exposure times (>1 second) and extremely short exposure times ($<10^{-5}$ second), the reciprocity law is not valid and the film experiences reciprocity failure. A thorough discussion of reciprocity failure is given in reference 11.

A large difference in the exposure time of reentry trails and star trails exists. In general, the effective exposure time (time interval for which 1 resolution area of the film is exposed) for reentries is on the order of 10^{-2} second and the effective exposure time for stars is on the order of 10 seconds. One way of determining the effective exposure time is to measure the half-half width of the star-trail image and divide four times this quantity by the trailing velocity of the star-point image across the emulsion. The half-half width is defined as the interval from maximum intensity at the center of the image to the point on either side where the intensity has decreased to half its maximum and central value. This is the method used in references 1 and 2. A reciprocity-failure correction for the time intervals t_s of the star and t_r of the reentry is then applied. A reciprocity curve is given in reference 12 from which the reciprocity-failure correction can be obtained for the Royal X Pan emulsion. A good reciprocity curve for the blue-sensitive single-coated medical X-ray film, extensively used in natural meteor work, has not been available, and no reciprocity-failure correction has been applied (ref. 13) to most of the resulting photometry. This practice, unfortunately, has been carried over to photometry of Royal X Pan film in some cases. (See refs. 14 and 15.)

The star-trail image does not result from a constant flux on the emulsion for a given increment of time, but is produced by a photon distribution which sweeps across the emulsion. This sweeping or trailing of the star image relative to the emulsion is produced by the rotation of the earth for nontracking spectrographs. The trail of a reentry image results from the motion, and hence the angular velocity relative to the spectrograph, of the reentries through the atmosphere.

Several tests of sweeping images across the emulsion at different angular rates were conducted to determine whether any film effects resulted from the use of a trailing source rather than an extended source. The test apparatus consisted of a collimated point source, a K-24 spectrograph, and a turntable-gearbox. The turntable-gearbox contained a synchronous motor and a reduction-gear train in a cabinet which allowed rotation of the camera past the point source at different angular rates. The scatter in the data, in general, was very large, mainly because of nonuniform trailing of the point source across the emulsion. Generally, the results indicated that for a typical star trail a

reciprocity correction factor of 2 to 4 (a factor which increases the uncorrected measured stellar irradiance) is needed for reciprocity failure between the effective exposure times of stars (10 seconds) and reentries (10^{-2} second) for Royal X Pan film. Calculations based on estimated optical transmission of the spectrograph and the manufacturer's values of film sensitivity support these results. The reciprocity results of several tests of high repeatability of nontrailing extended sources photographed on Royal X Pan film agree very closely with the reciprocity curve in reference 12. Preliminary work with photometry of star spectra has yielded fair agreement with irradiance measurements using an NBS-calibrated standard lamp only when corrections, by the half-half-width method, were applied. It was concluded that, by determining effective exposure times by the half-half-width method of reference 2 and using the manufacturer's reciprocity data, reciprocity-failure corrections to an accuracy of approximately 10 percent can be obtained. Reciprocity-failure corrections of 5-percent accuracy would probably be obtained from good data based on trailing-source effective-exposure times and taken from and applied to the same batch of film.

PHOTOMETRY OF A STELLAR STANDARD OF SPECTRAL IRRADIANCE

A method of absolute slitless spectral photometry has been discussed. A convenient and independent way of determining the accuracy of the photometry and associated calibrations exists. This determination of accuracy is simply the measurement of the spectral irradiance by photometry of a standard of spectral irradiance and the comparison of the measured values with the actual values. A star is a natural choice as a standard of spectral irradiance.

Slitless photometry has been performed on a spectrogram of the star Vega, the brightest star in the constellation Lyra. The spectrogram of Vega was obtained from a K-37 spectrograph (a 300-millimeter-focal-length version of the 178-millimeter-focal-length K-24 spectrograph) with a 300-line/millimeter objective grating. An enlargement of part of the spectrogram is shown in figure 9. The spectrogram was taken at Wallops Island, Virginia, on April 29, 1965. The zenith angle of Vega at the time of the exposure

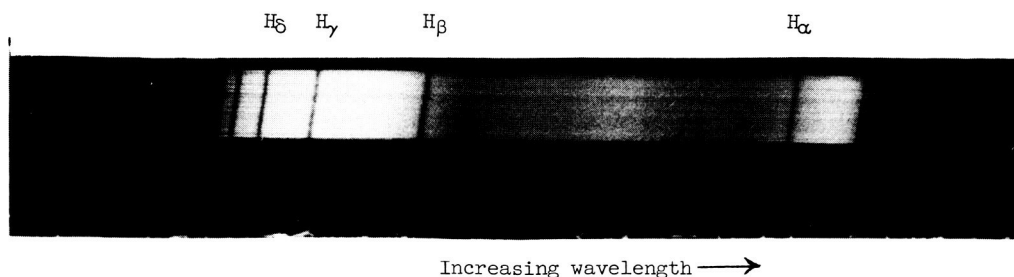


Figure 9.- Enlargement of first-order spectrum of star Vega taken with K-37 spectrograph. X 4.

was 15° . The K-37 spectrograph was calibrated immediately before the exposure to Vega. The density steps obtained from the K-37 spectrograph calibration by the irradiance sensitometer of figure 1 were used to obtain H and D curves at every 100-angstrom interval from 4100 to 6300 angstroms. Off-axis light-loss corrections from figure 7 were applied to each calibration and data point. A reciprocity failure correction factor of 3.72, obtained by using 65-micron half-half width of three star trails near the first-order spectrum image of Vega, was applied. The density of the zero-order star-trail images and the average density of the first-order spectrum image of Vega were approximately 0.5 above base fog. The spectral irradiance from Vega, measured at the spectrograph, is plotted in figure 10. Measured spectral irradiance outside the earth's atmosphere, corrected for atmospheric extinction by using the extinction coefficients of reference 16, has also been plotted in figure 10.

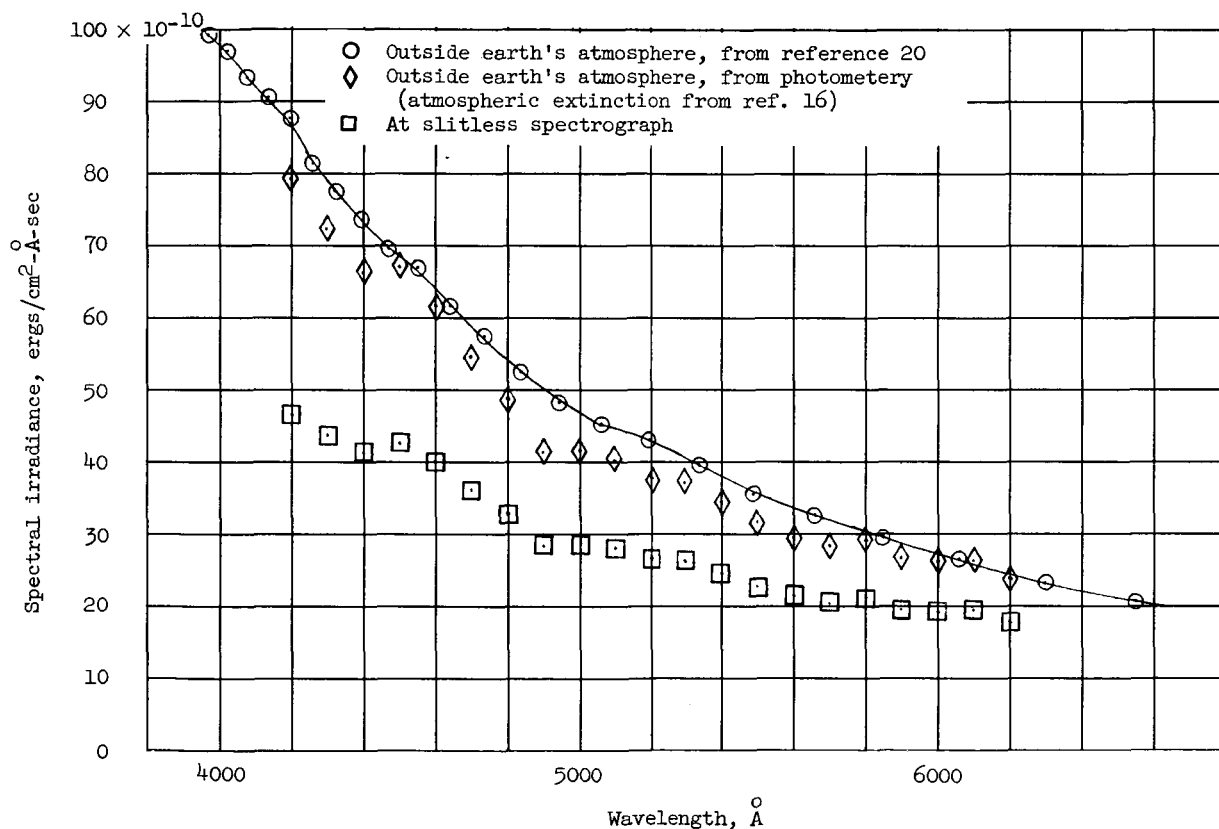


Figure 10.- Absolute spectral irradiance from star Vega.

Spectral energy measurements outside the earth's atmosphere have been determined by more than one observer for about 15 stars. These stars are the primary and secondary stellar standards of spectral irradiance. The star Vega is the primary stellar standard of spectral irradiance. Spectral energy measurements of Vega have been

reported by Hall in reference 17, by Bonsack and Stock in reference 18, by Code in reference 19, and originally by Kienle, Strassl, and Wempe in reference 20. The reported accuracy of these measurements in the visible wavelength region is 5 percent, and very good agreement exists among the observers.

The data points (diamond symbols) in figure 10 are compared with the spectral irradiance outside the earth's atmosphere as obtained from reference 20. The spectral energy measurements in reference 20 are presented in the form of stellar magnitude differences between the irradiance from the star being measured and the irradiance of the working standard (the mean irradiance of a selected group of nine early-type stars) at particular frequencies (inverse microns). These stellar magnitude differences were converted to common logarithms and added to the common logarithms of the standard curve. The standard curve for reference 20 was obtained from reference 21. The relative energy distribution in logarithmic form is now known. The energy distribution can be made absolute if the absolute energy at any wavelength is known. The absolute spectral irradiance from a star of 0 magnitude at 5556 angstrom is known and may be used. A value of $\log H_{5556} = -8.443$ as suggested by Dr. Cook, where H_{5556} is in units of ergs/second-centimeter²-angstrom, was used for the data of reference 20. The appropriate logarithmic factor is then added to account for the absolute stellar magnitude. The absolute stellar magnitude of Vega was obtained from reference 22. The spectral irradiance from Vega, as determined from reference 20, is also plotted in figure 10 (circular symbols).

RESULTS AND DISCUSSION

Absolute spectral photometry of spectrograms from moderate-aperture (5 to 30 centimeters) slitless spectrographs has been discussed and a method of photometry, using field calibration, has been described. Spectral photometry of a spectrogram of the stellar standard of spectral irradiance, Vega, has been performed with an average deviation of the measured values from the accepted values of 7.9 percent. The maximum deviation of any point in the wavelength interval from 4200 to 6200 angstroms was 16.3 percent. The photometry, based on a calibrated standard discussed previously, has been checked against an independent standard, Vega, and has been proven to be free of large or unknown systematic errors. The accuracy of this photometry is compared with the factor of 2 accuracy of reference 4 for which the instrumentation was similar.

The accuracy of the photometry can be expressed by the equation

$$\Delta H_{\lambda} = \sqrt{(\Delta D)^2 + (\Delta t_1)^2 + (\Delta t_2)^2 + (\Delta H_{\lambda}')^2 + (\Delta R)^2 + (\Delta M)^2 + (\Delta 0)^2 + (\Delta H_{\lambda}'')^2 + (\Delta A)^2} \quad (5)$$

where the accuracy of each of the following terms is as listed:

ΔD	variation in emulsion density	± 5 percent
Δt_1	uncertainty in sensitometer exposure time	± 5 percent
Δt_2	uncertainty in star exposure time	± 5 percent
$\Delta H_\lambda'$	uncertainty in sensitometer irradiance	± 10 percent
ΔR	uncertainty in reciprocity-failure correction	± 10 percent
ΔM	combined measuring errors	± 5 percent
$\Delta 0$	uncertainty in off-axis correction	± 5 percent
$\Delta H_\lambda''$	uncertainty in star irradiance	± 5 percent
ΔA	uncertainty in atmospheric extinction (excellent seeing)	± 5 percent

to give

$$\Delta H_\lambda = \pm 19 \text{ percent}$$

The significance of this method of photometry is that much better than "factor of 2 accuracy" absolute spectral irradiance measurements can be made with moderate-aperture spectrographs. Several of the sources of error in this photometry have not been fully evaluated and the uncertainties used in the following error analysis are estimated only to the nearest multiple of 5 percent.

The error statement and the photometry of Vega are in general agreement. It can be seen from the error statement that the error is not heavily dominated by one or two particular causes, but is fairly well distributed among all the inputs to the photometry. For this reason significant improvements in the accuracy of the measurements will not be easily achieved. The error analysis indicates that the major effort should be directed towards improving the sensitometer calibration and reciprocity-failure correction. It appears that with significant refinement in the sensitometer calibration and reciprocity-failure correction 10-percent accuracy photometry could be obtained.

The greatest problem in absolute spectral photometry now is the extension of the wavelength interval of good photometry. The new Royal X Pan Extended emulsion will allow the extension of the measurements to 6900 angstroms but, in general, the infrared-sensitive films are too slow to yield much data. Extension of the measurements into the near-ultraviolet region also poses problems. Data acquisition and calibration in this region, an important region for meteor and reentry work, are hampered by decreasing transmission of the atmosphere and optical glasses and by the lack of standards. The use of fast (f/1) quartz meniscus spectrographs promises to be a way of obtaining good spectral data in the near-ultraviolet region, 3300 angstroms, of the spectra. Spectral

photometry from 3300 to 6900 angstroms of fourth-magnitude stars should be attainable with an f/1 12-centimeter-aperture quartz meniscus spectrograph.

CONCLUDING REMARKS

The most useful quantitative spectral data, related to atmospheric reentry phenomena, have come from moderate-aperture (5 to 30 centimeters aperture) slitless spectrographs. A discussion of absolute slitless spectrophotometry is given, and a method of photometry with associated calibrations is presented for moderate-aperture slitless spectrographs. This method of spectrophotometry was devised for 20-percent accuracy in the visible-wavelength region. This is a factor of 5 reduction in uncertainty of measurement over previous absolute spectrophotometry using similar instrumentation for which accuracy statements have been made. The method of photometry has been applied to a spectrogram of the star Vega and has yielded spectral irradiance values, in the wavelength interval from 4200 to 6200 angstroms, with an average deviation of 7.9 percent from values in the literature. The maximum deviation of any of the data points, taken at every 100-angstrom interval, was 16.3 percent. The method of photometry presented herein is broader in scope than older methods of photometry in that the photometry can be related to a calibrated standard of spectral irradiance, or a stellar standard of spectral irradiance, or both. This method has been proven to be free of large or unknown systematic errors.

Langley Research Center,
National Aeronautics and Space Administration,
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